DIAGNOSTICS AND MONITORING OF THE OPERATING CONDITION OF STEAM-TURBINE BLADES

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A brief review of methods and means of diagnostics and monitoring of steam-turbine blades is made, informational criteria for determination of the defective status of blades are defined only by peripheral sensors, and a developed block diagram is presented for a system in the form of a software package to be used in monitoring the deformed status of blades and to ascertain their defective status.

Keywords: turbine-driven set, blades, rotor, diagnostics, sensors, discrete-phase method, vibration amplitude, steam turbine, probability, correlation, electric signals.

At the present time, the defective status of the blades of in-service steam turbines (ST) is monitored in conformity with [1] by use of basic and additional monitoring methods. Moreover, visual inspection and defect determination of each blade are carried out with use of commercial endoscopes, eddy-current and magnetic-flaw detectors, and certain other means and methods. This is very time-consuming work, which requires professional experience and responsibility of technical personnel. Moreover, essentially all monitoring methods call for monitoring and verification studies on the standing turbine, which, in turn, eliminates those natural dynamic and static loads that act on the blades under which defects develop and evolve within the latter.

A blade in which defective properties begin to appear under load will not therefore be mandatorily designated defective when inspected by these methods. Among the various methods presented in [1] for the diagnostics and monitoring of the deformed state of blades, accordingly, the contact-free discrete-phase method (DPM), which makes it possible to determine the individual deformed state of each blade of an operating runner, shows promise for in-service turbine-driven sets.

The principles of the DPM, and implementation of equipment modules and devices are presented in sufficient detail in [2]. The essence of the DPM consists in measurement of time intervals between pulses of root and peripheral sensors, their comparison with the geometric position of a specific blade in the runner at certain points in time, and corresponding interpretation of the values obtained in a region of mechanical stresses and strains.

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In [2], and in the "System for vibration measurement," which has been developed by the NPP "MERA" for the diagnostics and monitoring of steam- and gas-turbine blades, root sensors are used to determine the deformation characteristics of the blades of a turbojet engine. This is justified in the stage of experimental-adjustment operations, when it is required to maximize information on the behavior and characteristics of the blading. With the turbine-driven sets in operation, however, the installation of root sensors in the internal run of a set is occasionally difficult, and will restrict use of the DPM. The installation of merely one peripheral sensor in the impeller casing of the ST stage being monitored is technically an entirely feasible operation. Warning indicators [2] of the breakage of blades operating without root sensors, however, record only after-the-fact events, and do not warn of the appearance and development of a blade defect.

There are data on the shaping of root (reference) blade pulses by software/hardware [3] on the basis of the measured period of rotation of the turbine rotor. Such an approach to implementation of the DPM is fully justified in cases of slowly changing transitional modes, and selection of extrapolating polynomials, which in transitional modes, are considered most informative in the plan for exposing defective blade properties, is required, and will provide adequate spacing of pulse signals simulating the reference pulses of each blade. Replacement of actual processes by extrapolating functions to predict subsequent periods of revolution of the rotor will lead to a reduction in the accuracy of the measurements, complication of the hardware/software portion of the monitoring and diagnostics devices, and to diminution of their reliability.

In the mid-1980s, optoelectronic means of DPM implementation [4], which were intended to determine the strains of dynamically loaded blades of rotating runners by mea-

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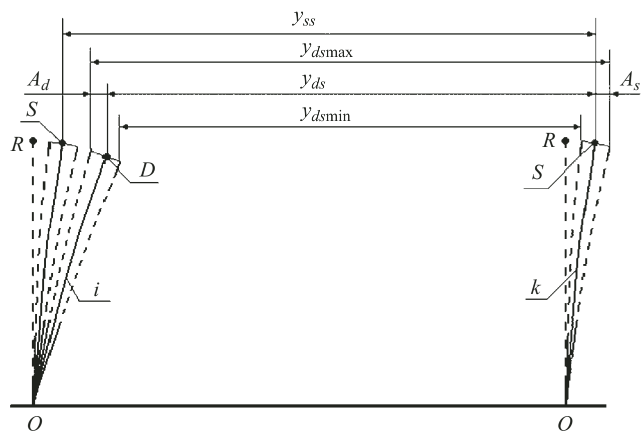

Fig. 1. Element of peripheral sweep of blade rim with two neighboring blades during operation of turbine-driven set.

surement of the angular positions of the ends of the blades, were proposed on the basis of developments expanding the functional potential of the DPM. The physical principle of the relationship between the reflecting properties of the materials on the quality of their machining and frequency of the electromagnetic radiation is based on these methods. The primary advantage of the optoelectronic discrete-phase method is the possibility of determining blade deformations caused by the highest forms of blade vibrations in the absence of root sensors. Rapid plotting of the optically active window of the optoelectronic transducer, however, does not permit widespread use of this method.

It is deemed that the logical path to implementation of an operationally acceptable version of the DPM consists in the fact that under conditions where one peripheral sensor capable of retaining its long-term serviceability is used, it would be possible to determine the required informational and diagnostic parameters.

In conformity with [1], the informational criteria required for diagnosis of the condition of in-service blades by use of the DPM are the vibration amplitudes and static coordinates of the ends of the blades. One of the following versions is recognized to provide the static coordinates of the end of a blade.

1. The coordinates of the peripheral static departure of the end from the radial direction of the axis of the blade. Root sensors, or use of octoelectronic transducers are introduced; as previously indicated, therefore, conditions for the implementation of operationally acceptable installation schemes are unfulfilled.

2. The coordinates of the end of the blade and their variation with respect to a fixed point on the rotor or web of the bladed impeller, for example, to a timing mark. The disadvantage of this alternate scheme is associated with the fact that the timing mark is formed, as a rule, in the most accessible area, which for ST is the zone of the generator bearing and exciter, which is approximately 5 – 10 m distant from the turbine stages being monitored. As a result, the twist of the generator and turbine rotors changes with varying load on the ST; this introduces a pronounced error to determination of the static coordinates of the ends of the blades.

3. The mutual coordinates of the ends of the blade, which are related to the average peripheral spacing or average time interval between the blades of the rotating runner and the estimate of its variation. This alternate scheme of determining the static coordinates of the ends of the blades best qualifies for construction of a monitoring and diagnostic system operating with a single peripheral sensor, since many interfering factors inherent to the other schemes are eliminated in the acquisition of informational parameters.

The peripheral sweep of the blade rim on which two neighboring blades are represented is shown in Fig. 1 to explain the approaches taken to modeling of the problem of determining quantitative estimates for implementation of the third alternate scheme of defining the coordinates of the blade ends.

With the turbine operating under centrifugal, steam, or gas forces, the elastic line OS of the blades occupies the averaged stationary position, which in the general case, may differ from the radial direction OR. In the presence of exciting forces, the blades participate in the oscillatory process that takes place relative to line OS. The averaged spacing between the ends of the blades is then determined by the value of yss. If, for example, a defect begins to develop in the ith blade, this will lead to a reduction in its stiffness, and, correspondingly, to a reduction in the safety factor and a change in the stress state. The position of the elastic line of the blade during its dynamic loading by steam, gas, and centrifugal forces will therefore begin to change.

The defective blade acquires additional bending, and oscillatory motions of the blade will begin to occur relative to a new elastic line OD with varying amplitude A_d. In that case, the spacing between the ends of the blades will be y_{ds}. The departure of the end of the blade from the initial defect-free state $\delta = y_{ss} - y_{ds}$, or the variation in the static mutual coordinates of the ends of the blades make it possible to judge the deformed state of the blade, and to a certain degree the extent of the damage that it has sustained; here, it is precisely this diagnostic symptom that is independent of the phase and frequency of blade oscillations. The existence of damping banded-wire connections to the runners of ST does not alter general approaches taken to solution of the problem, but does change only the vibration amplitudes and position of the elastic line of the blades to a certain extent.

With respect to the amplitude criterion for assessment of blade serviceability, it is possible, according to Fig. 1, to write

$$A_s = (y_{ss\max} - y_{ss\min})/4$$

for defect-free blades in good working condition.

In conformity with this formula, the average vibration amplitude of the blades can be determined for all characteristic operating modes of ST, and the maximum $A_{\max}$ and mini-

mum A_{min} vibration amplitudes of the blade, which when compared with the average amplitude, will yield the algebraic difference

$$\Delta = A_{max} - A_s = |A_{max} - A_s|$$

characterizing structural and procedural deviations during manufacture of the blades and blading of the runner, can be isolated after statistical analysis.

Considering the data derived from the average vibration amplitudes of the blades, the current average value of the vibration amplitudes A_{cur} of the blades is determined in the operating mode of the ST, and is compared with the average value. When $|A_{cur} - A_s| > \Delta$, the change in the vibration amplitude of the ith blade is constant, i.e., manifestation of a defect in the blade is recorded. For the interblade interval that has developed, the vibration amplitude of the defective blade is determined in the following manner:

$$y_{ds\max} = y_{ds} + A_d + A_s;$$

$$y_{ds\min} = y_{ds} - A_d - A_s.$$

Hence,

$$A_d = \frac{y_{ds\max} - y_{ds\min}}{2} - A_s.$$

The problem of determining informational criteria in any case therefore reduces to determination of interblade distances, or time intervals, whereupon it is assumed that the discrete-phase scheme under consideration for determination of the strain state of the blades, the vibration frequency of which is not a multiple of the rotational speed of the rotor, is constructed on the assumption that in the process of accumulating information, the ends of the neighboring blades will proceed past the peripheral sensor even if once in phases corresponding to two extremal values of their oscillatory processes, i.e., maximum $y_{ds\max}$ and minimum $y_{ds\min}$ spacings will be recorded between the ith defective and kth serviceable blades (Fig. 1). Then,

$$y_{ds} = \frac{y_{ds\max} - y_{ds\min}}{2}.$$

It is obvious that an increase in the time of acquisition will, with high probability, permit correct fixation of the maximum and minimum spacings between the blades, and, accordingly, determination of the interblade interval with the defective blade. Consequently, the time of acquisition of the informational parameter is limited, on the one hand, by the time required for development of the defect in the blade, and on the other, by the reliability of the measurements conducted. It is therefore necessary to determine that minimum time of information acquisition during which it is possible, with a given probability, to state that y_{ds} differs little from the serviceable value.

In conformity with the procedure proposed in [2], it is possible to admit that the vibrations of the ends of the neighboring blades are deterministic, or random stationary processes $y_i(t)$ and $y_k(t)$ with peak-to-peak oscillations of $2A_d$ and $2A_s$, respectively, and with random initial phases. Based on Fig. 1, the spacing between the ends of these blades can then be represented as

$$y_{ik}(t) = y_{ds} + y_i(t) + y_k(t).$$

The amplitude variations in the $y_i(t)$ and $y_k(t)$ processes, as previously noted, for extremal values

$$y_{ik\max} = y_{ds} + A_d + A_s$$

and

$$y_{ik\min} = y_{ds} - A_s - A_d.$$

Then,

$$y_{ik\max} - y_{ik\min} = 2(A_s + A_d).$$

On the condition that $y_{ik}(t)$ is referenced with respect to the same intervals equal to the time of a single revolution of the rotor, it is necessary to determine that number of N readings (periods of rotation of the rotor) such that the probability P of perceiving a distinction between the difference between the maximum and minimum values of the informational parameter $y_{ik}(t)$ and peak-to-peak sweep $2(A_d + A_s)$ does not exceed a certain assigned value (error) ε

$$P[\,2(A_d + A_s) - (y_{ik\max} - y_{ik\min})] \le \varepsilon.$$

In this general statement, the problem could be solved for known statistical characteristics of the oscillatory processes [2], such as the density of the probability distribution and correlation functions of the processes. Since these characteristics are known in advance, an estimate of P can be obtained only after measurements are taken. For a preliminary estimate of the number of readings required, it is possible to assume that the vibrations of the ends of the blades are purely harmonic with a random initial phase and random ratio of the vibration frequency to the rotational speed of the rotor (frequency of readings).

The vibrations of the ends of the ith and kth blades are then represented by the expressions

$$y_i = A_d \sin[2\pi(n + \varphi_i)]$$

and

$$y_k = A_s \sin[2\pi(n + \varphi_k)]$$

where φ_i and φ_k are the phases of the vibrations of the ends of the corresponding blades, and n is the multiplicity of the ratio of the vibration frequency of the ends of the blades to the rotational speed of the rotor.

The spacing between the ends of the blades is therefore determined as

$$y_{ik} = y_{ds} + \{A_d \sin[2\pi(n + \varphi_i)] +$$
$$+ A_s \sin[2\pi(n + \varphi_k)]\} = y_{ds} + y_v.$$

Thus, the term y_v will be formulated, and extremal increments to the spacing y_{ds} determined. In that case, the probability P can be determined by the Monte-Carlo method of

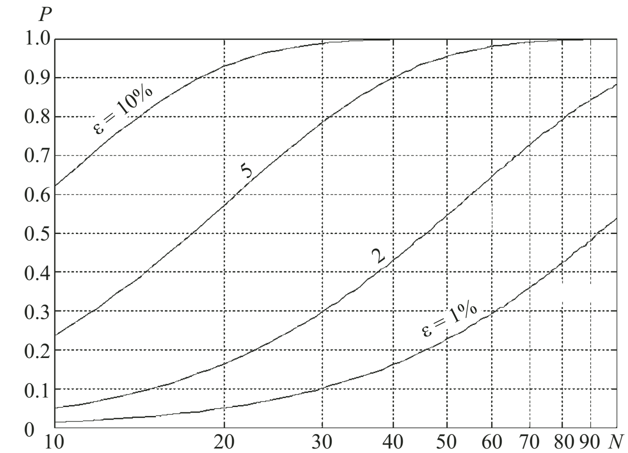

Fig. 2. Diagram showing dependence of probability P of determination of interbalde interval on number N of periodis of rotor revolution for different values of error ε.

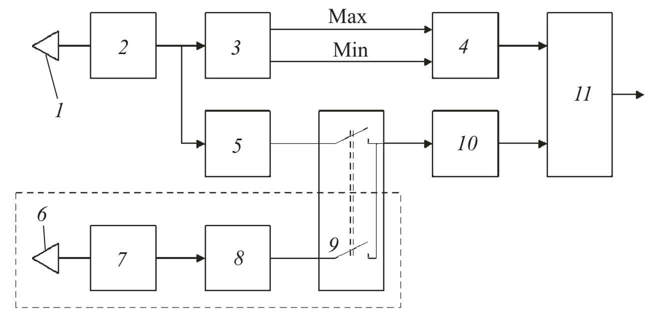

Fig. 3. Block diagram of system for diagnosis of defective blades.

statistical tests [5], using computer modeling for which 10^5 tests are conducted for each number of successive periods of revolution of the rotor (i.e., N rotor revolutions is considered one event repeated 10^5 times in the computer experiment in question). In each of the tests, we calculated N values of y_{ik} (the subscript $ik = 1, 2, ..., N$) from the formula

$$y_{ik} = y_{ds} + y_{\nu}.$$

Moreover, it was assumed that y_{ds} = const. The multiplicities n and the phase values φ_i and φ_k for each test were assigned using three different uncorrelated generators of random numbers with a uniform distribution. In all, 90 series of these tests were conducted for a number of periods of revolution of the rotor $N = 10, 11, 12, ..., 99, 100$. In each series, we calculated the probability P for different values of the error ε. Figure 2 shows the results of the calculations.

The curves (Fig. 2) enable us to establish the probability that in analyzing N periods of revolution of the rotor, the statistical error of determination of the interblade interval will not exceed *a priori* the value of ε selected. For an allowable error $\varepsilon = 5\%$ and $P = 0.95$ selected, the required number of readings will be 50. This implies that the time during which the rotor completes 50 revolutions will be 1 sec at operating ST rotor speeds of 3,000 rpm.

Using the curves shown in Fig. 2, it is possible to roughly select the number of rotor turns required in each specific case, i.e., the time of information acquisition, in other words, if the approximate time of defect development is known, it is possible with both a high and low accuracy and reliability to assess the deformed state of the blades.

Here, the majority of authors studying the failure processes of blades (for example, the development of such a defect as a crack) arrive at the fact that the time for a defect to develop from the start of its reliable recording by DPM instruments to rupture of the blade will occupy from several tens of minutes to several tens of hours, depending on the duration of the turbine's operation under conditions that excite resonant vibrations.

Results of the modeling therefore indicate that determination of the required diagnostic criteria by the discrete-phase method by a single peripheral sensor is entirely feasible.

Supported by the theoretical premises of the DPM and also the modeling that we have performed, we formulated a block diagram of a monitoring system for the deformed state of blades [6] based on the principle of the measurement of the real-time intervals (spacings) between the ends of rotating blades, determination of the maximum and minimum values of each spacing and the average value of each spacing, and their comparison with the spacings for each rotor turn of the turbine-driven set averaged over the runner.

The block diagram (Fig. 3) functions in the following manner. Peripheral sensor *1*, which is mounted in the casing of the turbine-driven set above the mechanical trajectories of the ends of the blades, generates an electric signal, which with the use of shaper *2*, is transformed into a rectangular pulse. The time intervals τ_i between rectangular pulses, which correspond to the peripheral spacing between the ends of the blades, are transformed into a digital code in block *3*. In this same block, the maximum and minimum values for each spacing are determined from N current turns of the rotor. The extremal values obtained for each spacing are entered to block *4*, where the averaged tis value of each spacing is determined in conformity with the expression

$$\tau_{si} = (\tau_{i\,\max} + \tau_{i\,\min})/2.$$

Moreover, the rectangular pulses from shaper *2* are fed into block *5*, where the time intervals ti are summed over N rotor turns, after which the period of revolution of the rotor over the N turns is determined as

$$T_s = \frac{1}{N}\sum_{j=1}^{N}\sum_{i=1}^{K}\tau_i.$$

Where the technical installation of the turbine-driven set enables us to establish sensor 6 as a timing mark of the rotor, its electric signals will transformed by shaper *7* into rectan-

gular pulses, which enter block *8* where the average period of revolution of the rotor over N turns is then determined as

$$T_s = \frac{1}{N} \sum_{j=1}^{N} T_j,$$

where T_j is the time of the jth period of revolution.

Switching block *9* ensures the required operating regime of the installation both with and without the timing-mark sensor. The T_s values obtained in block *10* are divided by the number of blades K in the runner, and the average spacing along the runner during N rotor turns is thereby determined

$$\tau_s = T_s/K.$$

τ_{si} and τ_s are then compared one with the other in comparison block *11*. If ts differs from tsi by a certain threshold value p, a signal warning of the appearance of a defect in one or several of the blades is generated at the output of block *11*.

Fig. 4. External appearance of SMSTB electronics unit.

The system for monitoring the deformed state of steam-turbine blades (SMSTB), the external appearance of which is shown in Fig. 4, was developed on the basis of the proposed algorithm and block diagram.

Communication between the SMSTB and a personal computer via a sequential RS-232 (RS-485) interface is possible for monitoring of the current condition of blades, approximate analysis of their serviceability, storage and archival storage of their in-service status, official reporting of inspection results, and issuance of a technical rating for the blade runner. Special software, which makes its possible to conduct in-service diagnostics of the blades in real time, has been developed to make this possible. The operator menu of the SMSTB, in which the current status of the blade rim in the 30 stages of a PT60-130/13 is presented, is shown as an example in Fig. 5. Moreover, the SMSTB calls for an autonomous internal storage device, which is activated after transmission of a warning signal, and records the dynamics of blade-defect development. The date, time, and strain state of

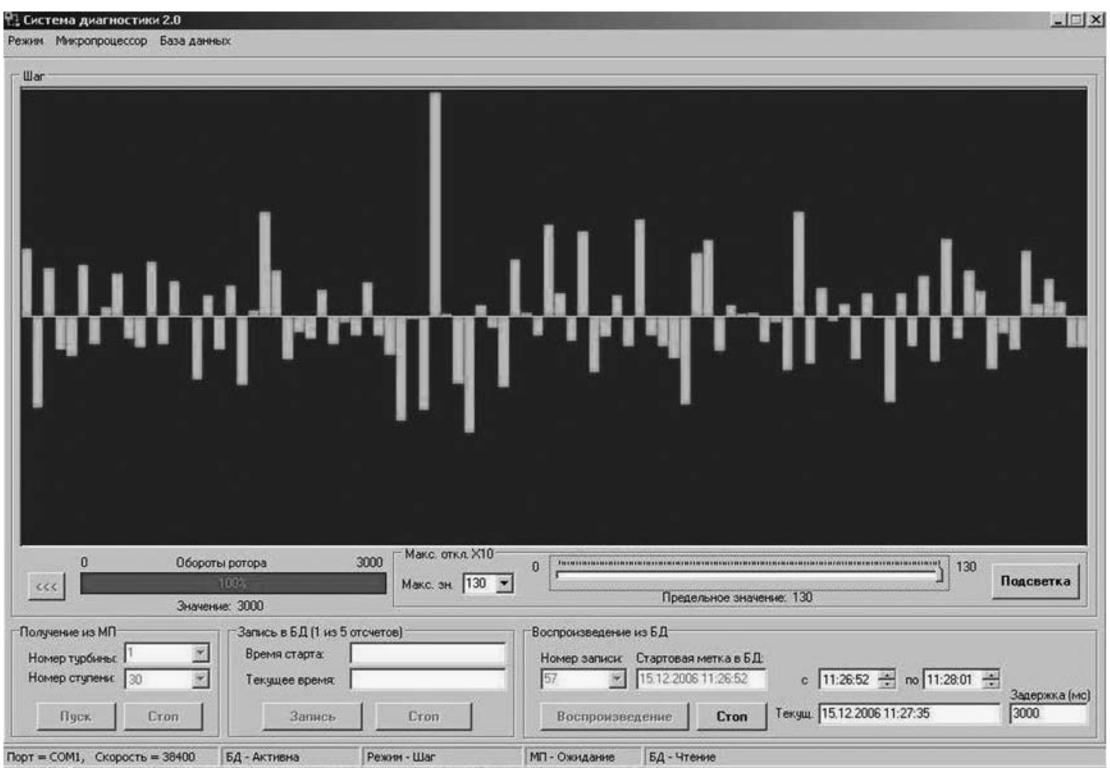

Fig. 5. Current operator's menu for SMSTB.

all blades in the runner are written here to the internal self-powered working storage unit.

The system for monitoring the strain state of the steam-turbine blades has been developed and implemented on a modern radio-technical-component base; this made it possible to obtain a reliable device with in-service adaptation for runners with different numbers of blades. The principle of the existence and propagation of electromagnetic super-high-frequency radiation in waveguide systems is employed in the sensors used for the SMSTB. The materials and structural components selected for these waveguide sensors enable us to obtain satisfactory results to temperatures of 1000°C and higher. The SMSTB, which are fitted with waveguide sensors, also permit monitoring of the high-temperature stages of ST, including the integrity of the entirely milled band of the runner, and the variation in the gap between the band and internal surface of the casing. A signal warning of the development of a defect in one or several blades in the form of warning-light and alarm signals is transmitted to the dispatcher-operator's desk.

The TÉTs VAZ has installed SMSTB in various ST to monitor the condition of the blades in the final stages. During the period from 2004 through 2006, the system was finalized under operating conditions, and a set of statistical data on variations in informational criteria was developed for various ST operating modes. Surpassings of settings entered to the SMSTB, i.e., deviations of current distances between the ends of the rotating blades and their average value (1.5 mm — warning, and 2 mm — alarm) were not recorded after the indicated time interval.

A block diagram of the software package, which is scheduled to go into service at the TÉTs VAZ in the fourth quarter of 2007, is being developed for automated acquisition of data on the in-service condition of the blades within the stages being monitored, and exposure of defective status of the blades. The software package is shown in Fig. 6, and to date, it has been implemented in five SMSTB, the data from which should be fed into a server, whose function it is to receive and process the data, transmit signals relative to the surpassing of thresholds (settings), store archival data, and transfer information to users in the local computer network.

CONCLUSIONS

1. Methods and means of the diagnostics and monitoring of steam-turbine blades are briefly reviewed.

2. Selection and use of an alternate DPM scheme with a single peripheral information sensor are substantiated.

3. Informational criteria for detecting the defective status of steam-turbine blades are determined with the use of a lone peripheral sensor.

4. Results of computer modeling are presented for determination of the probability of detecting an informational parameter as a function of the time of data acquisition.

5. A block diagram developed for a system that monitors the deformed state of steam-turbine blades for various steam turbines at the TÉTs VAZ is presented and described.

6. A block of the software package used to expose the defective state of blades is presented.

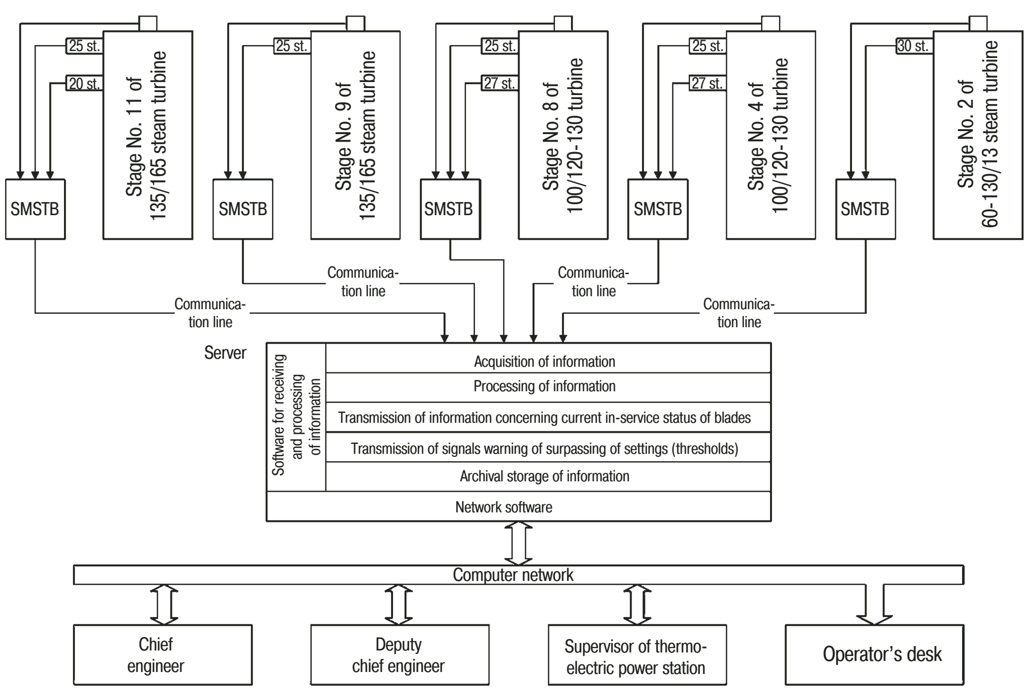

Fig. 6. Schematic diagram of software used to expose defective state of blades at TPP at VAZ.

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